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OPTICAL READHEAD

The present invention relates to a detection unit for
an interferometer.

In an interferometry apparatus, two coherent beams are
interfered together to form a spatial fringe field in
the form of interference fringes at a detection unit,
which contains electronics, such as photodiodes and
amplifiers etc.

It would be advantageous to have a detection unit in
which no electronics are required. This would allow
the size of the detection unit to be reduced.
Furthermore, if the detection unit does not have
electronics the problem of electronic noise from other
components (such as motors) is eliminated.

The electronics in the detection unit are a heat source
which can cause measurement error due to expansion of
parts of the apparatus such as the detection unit
itself and the system which the interferometer is
measuring. Thus it is desirable to remove this heat
source.

The present invention provides interferometry apparatus
comprising:
    a measurement light beam and a reference light
beam which interact with each other to cause a spatial
fringe pattern;
    an optical device which interacts with the spatial
fringe pattern, such that light is spatially separated
into different directions;
    and wherein the intensity modulation in two or

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more directions of the spatially separated light is phase shifted.

The optical device may interact with the spatial fringe pattern such that within a fringe of the spatial fringe pattern, light is spatially separated into different directions.

The light may be spatially separated over at least a portion of one or more fringes of the spatial fringe pattern.

The light may be spatially separated into two or more sub-beams.

The spatially separated light in different directions may be detected by optical detectors. The spatially separated light may reach the detectors via optical fibres.

At least one focussing means may be provided to focus the spatially separated light in the different directions into the optical fibres or onto the optical detectors.

The optical device may comprise at least one fresnel lens.

The optical device may be a diffractive device.

In one embodiment, the optical device comprises a plurality of segments, wherein light from the spatial fringe field incident on each segment is diffracted into a different diffraction direction, thereby

spatially separating the spatial fringe field.

The optical device may have a plurality of segments
having different structures, the different segments
being arranged in a repeating pattern. Two or more
segments of the plurality of the segments may comprise
blaze gratings, wherein the blaze gratings extend in
different directions. One of the plurality of segments
may have no structure.

The optical device may comprise a diffractive optical
element.

The optical device may be a refractive device.

In one embodiment, the optical device may comprise a
plurality of segments, wherein light from the spatial
fringe field incident on each segment is refracted into
a different direction, thereby spatially separating the
spatial fringe field.

The optical device may have a profiled surface, such
that refraction at the profiled surface causes spatial
separation of the spatial fringe field.

The optical device may be configured such that the
phase difference of the spatially separated light beam
enables outputs of the detectors to be combined to
generate two signals with a known phase difference.
The optical device may be configured such that the
phase difference of the spatially separated light beam
enables outputs of the detectors to be combined to
generate quadrature signals.

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Embodiments of the invention will now be described by way of example and with reference to the accompanying drawings in which:

 Fig 1 illustrates a prior art interferometry apparatus;

 Fig 2 is a representation of the detection unit of the present invention;

 Fig 3 illustrates the phase difference of the four resultant beams produced in the apparatus shown in Fig 1;

 Fig 4 illustrates the cosine fringes on a DOE to provide four beams;

 Fig 5 illustrates the convolution of the complex amplitude of the grating Ωgrating(ω) and complex amplitude of the fringes Ωfringes(ω) to produce the output complex amplitude Ωout(ω);

 Fig 6a illustrates the real and imaginary parts of the grating amplitude for a first solution;

 Fig 6b illustrates the phase and intensity of the grating for the first solution;

 Fig 6c illustrates the output intensity against angular displacement of the four resulting beams for the first solution;

 Fig 7a illustrates the real and imaginary parts of the grating amplitude for a second solution;

 Fig 7b illustrates the phase and intensity of the grating for the second solution;

 Fig 7c illustrates the output intensity against angular displacement of the four resulting beams for the second solution;

 Fig 8a illustrates the real and imaginary parts of the grating amplitude for a third solution;

 Fig 8b illustrates the phase and intensity of the grating for the third solution;

Fig 8c illustrates the output intensity against angular displacement of the four resulting beams for the third solution;

Fig 9 illustrates the convolution of the complex amplitude of the grating Ωgrating(ω) and the complex amplitude of the fringes Ωfringes(ω) to produce an output complex amplitude Ωout(ω) for a three phase grating;

Fig 10a illustrates the real and imaginary parts of the grating amplitude for a 3-phase splitting grating;

Fig 10b illustrates the phase and intensity of the grating for a 3-phase splitting grating;

Fig 10c illustrates the output intensity against angular displacement of the four resulting beams for a 3-phase splitting grating;

Fig 11 illustrates an optical device having a profiled upper surface;

Fig 12 illustrates the optical device of Fig 11 showing the deflected light paths;

Fig 13 illustrates a perspective view of an optical device including blazed gratings;

Fig 14 is a plan view of the optical device of Fig 13;

Fig 15 is a side view of the optical device of Fig 13;

Fig 16 is a schematic illustration of a birefringent optical device having a profiled upper surface; and

Fig 17 illustrates light passing through the optical device of Figs 13-15 being focused into optical fibres by a Fresnel zone plate.

Fig 1 illustrates a prior art interferometer, which is

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described in GB2296766. A light source 1 produces a
coherent light beam 2 directed towards a polarising
cubic beam splitting device 3. The polarising beam
splitter 3 produces from the light beam 2 a first,
5   transmitted beam 2a and a second reflected beam 2c. Use
of the polarising beam splitter 3 ensures that the
transmitted and reflected beams 2a, 2c are orthogonally
polarised with respect to each other. The first
transmitted beam 2a, which in this example forms the
10 measuring arm of the interferometer, passes straight
through the polarising beam splitter 3 and is directed
towards a retroreflector 6 attached to a moving object
(not show) the position of which is to be measured by
the interferometer. The retroreflector returns the
15 light beam as beam 2b to the polarising beam splitter
3. The return beam 2b is transmitted through the
polarising beam splitter and passes onwards towards a
detection unit 4.

20 The polarising beam splitter 3 also produces a second,
reflected beam 2c, which forms the reference arm of the
interferometer. The reflected beam is directed towards
a second retroreflector 7 which is fixed with respect
to the beam splitter 3 and then reflected by the
25 retroreflector back to the polarising beam splitter. On
its return the beam 2d is reflected from the polarising
beam splitter towards the detection unit.

As previously mentioned, this arrangement causes beams
30 2b and 2d to have different polarisation states.

A birefringent prism 8 refracts the beams 2b, 2d
through different angles causing them to converge and
the polarising element 9 mixes their polarisation

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states so that they interfere and generate a spatial
fringe field.

The detection unit 4 is placed in the path of the
5   overlapping beams to receive the spatial fringe field.
The detector used is an electrograting. Such a
detector is known from our European Patent No. 0543513
and consists of a semiconductor substrate upon which a
plurality of elongate, substantially parallel
10   photosensitive elements are provided.

The present invention provides a detection unit in
which signals are created from the spatial fringe field
without the requirement of an electrograting. Fig 2
15   illustrates a detection unit 10 comprising a
diffractive optical element (DOE) 12, a lens 14 and
four detectors 16,18,20,22. A spatial fringe field 24
comprising cosine fringes is formed at the detection
unit 10 by the interference of two coherent light beams
20   26,28 (i.e. the measurement arm and reference arm of an
interferometer as shown in Fig 1).

When the detection unit 10 is illuminated by the cosine
fringes four beams 30,32,34,36 are formed which are
25   focused by lens 14 onto detectors 16,18,20,22. The
lens could be integral with the DOE. Alternatively
four individual lenses could be used. The four beams
are 90° out of phase and thus the intensities detected
at the detectors vary in quadrature as the cosine
30   fringes are translated across the detection unit.

Fig 3 illustrates the intensity variation at the
detectors 16,18,20,22 over time as the cosine fringes
are moved laterally relative to the detection unit 10.

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It can be seen that the intensities at each detector 16,18,20,22 vary cyclically and are 90° out of phase with one another.

5   The invention is not restricted to producing four light beams. For example the DOE may be designed to create three beams which are $\pi/2$ or $4\pi/3$ out of phase depending upon the design. The output of the detectors may be combined to generate quadrature signals which

10   may be used to interpolate the magnitude and direction of relative movement between the fringes and the periodic light pattern. The method.of combining outputs from three detectors to generate such quadrature signals is disclosed in our earlier

15   published International Patent Application WO87/07944.

The mathematical specification of the DOE may be calculated as follows with reference to Figs 4-8.

20   Fig 4 shows cosine fringes 24 incident on a DOE 40 to provide four beams a,b,c,d which vary in intensity I_1, I_2, I_3, I_4 and quadrature as the cosine fringes are translated relative to the readhead. The cosine fringes may be described by the equation:

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$$Ufringes(x) = \cos \frac{2\pi(x - \Delta x)}{p}$$

where x is the linear displacement; Δx is the change in linear displacement; and p is the periodicity of the complex amplitude field produced by the interference of

30   the two incident beams. The periodicity of the intensity interference pattern is p/2.

The output complex amplitude $\Omega out(\omega)$ of the DOE is

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given by the Fourier transform of the product of the cosine fringes (Ufringes (x)) and the DOE as shown below. Output coordinates are

5    $\underline{x} = \underline{\omega}.\lambda z$

where λ is the wavelength of the incident light, ω is the spatial angular frequency of the co-ordinate system, and z is the propagation distance.

10   Ωout(ω)   =   Ft[Ufringes(x).Ugrating(x)]

              = Convolution[Ft[Ufringes(x), Ft[Ugrating(x)]

15   = Convolution[Ωfringes(ω), Ωgrating(ω)]

where Ft is the Fourier Transform.

The form of the complex amplitude of the grating
20   Ωgrating(ω) must be such that when convolved with the complex amplitude of the fringes Ωfringes(ω) it produces at least four beams. Furthermore as the intensity of the four beams is required to vary in quadrature with Δx, it is necessary for the complex
25   amplitude of each beam to consist of at least two components so that the required phase relationship can be imposed. (Single component beams are not suitable as they would have constant intensity.) A possible solution is illustrated in Fig 5. Fig 5 illustrates
30   the convolution of Ωgrating(ω) and Ωfringes(ω) to produce Ωout(ω). A-E are complex numbers and

$\phi = 2\pi\Delta x/p$

35   The output intensity is given by the square of the

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modulus of the output amplitude. The intensities of the four beams can then be equated to the required quadrature signals:

5    $I_n(\Delta x) = 1 + q \, \text{Cos}(2\phi + n\pi/2)$

where q is the AC modulation with a DC level of unity.

Let I_1 be the modulus squared of the complex amplitude
10   of the first output beam resulting from the combination of the incident beams and the property of the DOE, then

$$I_1 = |\tfrac{1}{2}(Ae^{-i\phi}+Be^{+i\phi})|^2$$

$$= \tfrac{1}{4}(Ae^{-i\phi}+Be^{i\phi})(A^*e^{i\phi}+Be^{-i\phi})$$

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This can be related to the required modulated intensity terms by

$$I_1 = \tfrac{1}{4}(|A|^2+|B|^2+AB^*e^{-2i\phi}+A^*Be^{2i\phi})$$

20   $$= 1 + q\text{Cos}2\phi = 1+\frac{q}{2}(e^{2i\phi}+e^{-2i\phi})$$

Similarly

$$I_2 = \tfrac{1}{4}(|B|^2+|C|^2+BC^*e^{-2i\phi}+B^*Ce^{2i\phi})$$

25   $$= 1+q\text{Cos}(2\phi+\pi/2) = 1+\frac{q}{2}(e^{i(2\phi-\pi/2)}+e^{-i(2\phi-\pi/2)})$$

$$I_3 = \tfrac{1}{4}(|C|^2+|D|^2+CD^*e^{-2i\phi}+C^*De^{2i\phi})$$

$$= 1+q\text{Cos}(2\phi-\pi) = 1+\frac{q}{2}(e^{i(2\varphi-\pi)}+e^{-i(2\varphi-\pi)})$$

$$I_4 = \tfrac{1}{4}(|D|^2+|E|^2+DE^*e^{-2i\phi}+D^*Ee^{2i\phi})$$

$$= 1+q\text{Cos}(2\phi-3\pi/2) = 1+\frac{q}{2}(e^{i(2\phi-3\pi/2)}+e^{-i(2\phi-3\pi/2)})$$

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Thus

$$\tfrac{1}{4}AB* = \frac{q}{2} \text{ and } \tfrac{1}{4}A*B = \frac{q}{2}$$

5   $$\tfrac{1}{4}BC* = \frac{q}{2}e^{+i\pi/2} \text{ and } \tfrac{1}{4}B*C = \frac{q}{2}e^{-i\pi/2}$$

$$\tfrac{1}{4}CD* = \frac{q}{2}e^{+i\pi} \text{ and } \tfrac{1}{4}C*D = \frac{q}{2}e^{-i\pi}$$

$$\tfrac{1}{4}DE* = \frac{q}{2}e^{+i3\pi/2} \text{ and } \tfrac{1}{4}D*E = \frac{q}{2}e^{-i3\pi/2}$$

10
The equations on the right hand side are just complex
conjugates of the left hand side ones and can be
neglected.

15   Starting with an arbitrary A value.

$$B = \left(\frac{2q}{A} \right)^*$$

$$C = \left((2q/B)e^{i\pi/2} \right)^*$$

20   $$D = \left((2q/C)e^{i\pi} \right)^*$$

$$E = \left((2q/D)e^{i3\pi/2} \right)^*$$

Now let A=1, q=½, then the values of A-E are

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A = 1
B = 1
C = -i
D = +i
30   E = -1

This system is illustrated in Figures 6. Fig 6a shows
the real and imaginary parts of the grating amplitude

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against displacement x, Fig 6b shows the phase and intensity of the grating against displacement x and Fig 6c shows the output intensity in the spatial frequency co-ordinate system (ω).

Two alternative solutions are also possible, which differ only in the order of the phases. These are illustrated in Figs 7 and 8.

Fig 7a shows the real and imaginary parts of the grating amplitude against displacement x, Fig 7b shows phase and intensity of the grating against displacement x and Fig 7c shows the intensity in the spatial frequency co-ordinate system (ω) for the four resulting beams a,b,c,d for the values of A-E below:

$A = 1$

$B = e^{i0\pi/2}$ /A

$C = e^{i1\pi/2}$ /B

$D = e^{i3\pi/2}$ /C

$E = e^{i2\pi/2}$ /D

Thus

$A = 1$ $B = 1$ $C = i$ $D = -1$ $E = 1$

Fig 8a shows the real and imaginary parts of the grating amplitude against displacement x, Fig 8b shows phase and intensity of the grating against displacement x and Fig 8c shows the intensity in the spatial

frequency co-ordinate system (ω) for the four resulting beams a,b,c,d for the values of A-E below:

A = 1

5      $B = e^{i0\pi/2}$ /A

$C = e^{i2\pi/2}$ /B

$D = e^{i1\pi/2}$ /C

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$E = e^{i3\pi/2}$ /D

Thus

15   A = 1   B = 1   C = -1   D = -i   E = 1

It is also possible to use the D.O.E. to produce three resultant beams. A possible solution is illustrated in
20   Fig 9 and the equations below.

A = 1

$B = e^{-i.1.\pi/2}$ /A
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$C = e^{i.0.\pi/2}$ /B

$D = e^{i.1.\pi/2}$ /C

30   A = 1   B = -i   C = i   D = 1

Fig 10a illustrates the real and imaginary parts of the grating amplitude for a three phase splitter grating,

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Fig 10b illustrates the phase and intensity of the
three phase splitter grating and Fig 10c illustrates
the output intensity against angular displacement (ω)
for the three output beams a,b.c.

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The above solutions are specific analytical solutions.
Numerical optimisation of the DOE will typically use a
computer and produce designs that may not be of the
above form but may make the DOE easier to make and use.

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An alternative optical device for forming a plurality
of light beams from spatial fringe field will now be
described with reference to Figs 11 and 12.

15   Fig 11 illustrates an optical device 50 comprising a
transparent, eg glass, element 52 with a profile 54 on
one surface comprising a repeating pattern of three
surfaces 56, 58, 60 of equal distance angled at for
example 120° from one another.

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This profile may be formed from a saw tooth profile, in
which the top third is removed (for example, by
polishing).

25   A spatial fringe field comprising cosine fringes 62 is
formed at the optical device 50 by the interference of
two coherent light beams 64,66. Fig 11 shows cosine
fringes 62 incident on the optical device 50. Light
incident on the profiled optical device is refracted in
30   three different directions 68, 70, 72 by the three
angled surfaces, as shown in Fig 12. The period of the
optical device 74 is equal to the period of the cosine
fringes 76, resulting in the three resultant light
beams having different phases of 0°, +120° and -120°.

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Detectors (not shown) are provided to detect the three
resultant light beams 68,70,72. Alternatively, optical
fibres may be provided to couple the three resultant
5   light beams to their respective remote detectors.

In a reverse arrangement, the coherent light beams
64,66 are incident on the plane face of the optical
device, so that the light travels across the profiled
10   glass/air boundary from the glass side. In this
arrangement the angle of incidence of the light beams
64,66 will be greater than the arrangement illustrated
in Figs 11 and 12 to produce a fringe pitch in the
glass which is equal to the period of the profiled
15   surface.

The incident beams which interfere with each other to
produce an interference pattern do not have to be at an
angle to one another. Fig 16 illustrates an embodiment
20   in which the optical device 150 is made from a
birefringent material which has a polaroid material 151
coated onto its profiled surface 158. Two parallel
beams 164,166 which are orthogonally polarised are
incident on the optical device, and are refracted by
25   differing degrees by the birefringent material. The
beams are thus no longer parallel when they meet and
interfere at the polarising coating to form an
interference pattern. The interference pattern
interacts with the profiled surface as previously
30   described with reference to Figs 11 and 12.

Another type of profiled optical element will now be
described with reference to Figs 13-15. In this
embodiment, the optical device 80 comprises a

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transparent element 82, e.g. glass, with a profiled
surface 84.

The profiled surface 84 of the optical device is
5   divided into a repeating pattern of segments 88,90,92,
the pattern of segments extending parallel with the
direction of the light fringes 86. Figs 13 and 14 show
the repeating pattern of segments. Fig 13 is a
perspective view of the optical device and Fig 14 is a
10   plan view. Each repeatable section of the pattern
comprises a first segments 88 in which there is no
structure, a second segment 90 in which there is a
blazed grating extending in a first direction (shown by
arrow A in Fig 14) and a third segment 92 in which
15   there is a blazed grating extending in a second
direction (shown by arrow B in Fig 14).

Light incident on the different segments of the
profiled surface of the optical device is diffracted
20   into different directions. Light incident on the first
segment without any structure passes straight through
the optical device (i.e. 0th order of diffraction).
Light incident on the second and third segments is
refracted at different angles.
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Fig 15 is an end view of the optical element of Figs 13
and 14. Light 94 incident on the top face of the
optical device 80 passes straight through segment 88
(without structure), is diffracted in a first direction
30   passing through the segment 90 (with a blazed grating
in a first direction) and is diffracted in a second
direction passing through the segment 92 (with a blazed
grating in a second direction). The light beams
produced by the three segments are focussed by lens 96

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into three light spots 98,100,102 which are transverse
to the direction of the repeating pattern of segments.
As light incident on each of the segments 88,90,92 each
relates to a different part of the cosine fringes, the

5   three light spots will each have different phases, i.e.
0°, +/-120°.

Use of a blazed grating has the advantage that the lens
96 may be incorporated into the optical device 80 by

10   superimposing a Fresnel zone plate onto the blazed
grating, thus reducing the total size of the system.

Fig 17 illustrates part of the Fresnel zone plate which
focuses light into the optical fibres. The zone plate

15   comprises sets of sections A,B,C with each section of a
given set focusing the light to a given focal point.
Difference sets of sections focus light to different
focal points. The Fresnel zone plate may be configured
so that the focal points are arranged either parallel

20   or transverse to the plane of the optical fibre. Fig
17 shows light diffracted by a first set of segments 88
of the blazed grating being focused into a first
optical fibre 170, light diffracted by a second set of
segments 90 of the blazed grating being focused into a

25   second optical fibre 172 and light diffracted by a
third set of segments 192 of the blazed grating being
focused into a third optical fibre 174.

A coherent optical fibre bundle may replace both the

30   optical device and the discrete optical fibres. In
this case one end of the individual optical fibres in
the bundle are positioned adjacent the spatial fringe
field and spaced so that light of different phases
travels through different optical fibres to different

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detectors.

If heat from the electronics is acceptable then
photodetectors could be used instead of the optical
5   fibres. Here the photodetectors could be separate, or
housed within the same unit or they may even have a
common substrate as in quadcells or linear arrays.

Although Figs 11-17 illustrate transmissive systems, a
10   reflective optical device may also be used in the
invention.

All of the above embodiments provide alternatives for
an opto-electronic grating, thus providing a detection
15   unit in which no electronics are required.
Furthermore, as the detectors may be provided remotely
from the detection unit (i.e. by use of optical
fibres), the size of the readhead may be greatly
reduced.
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The detection units described above are suitable for
use with any interferometer in which a spatial fringe
field is produced.